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Study on one-shot process for wood-based composites

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Abstract

Environmental changes force industries to use renewable and degradable materials for lightweight solutions to solve weight and therefore CO2. One highly prioritized topic is the combination of wood materials with biodegradable plastics. Especially when processing these materials, it is essential to develop efficient processes to reduce obstacles and enable the application in serial use. To take advantage of the mechanical behaviour of the wood structure it is necessary to investigate the combination of thin solid wood with plastic. Regarding large-scale production, an injection moulding process is addressed in this study. When processing raw material cutting operations are used. To use the shear cutting process has several advantages: it is a cost effective process with short cycle times. Also no thermal influence or water immersion occur on the working material (like in laser beam or water jet methods), so material sensitive on this can be worked by shearing. But as a disadvantage a working force is applied. This work aims to show the findings this working fore on 5mm wood solids and the influence of the created surface on the bonding between plastic and wood cutting edge. The process connections and dependencies of shear cutting and injection moulding are investigated. Different wood materials were used to analyse the effects of cutting and material parameters (e.g. moisture, forces) on the cutting edge quality (e.g. structural damage). To detect the effect of different cutting edge qualities on the joint between wood and plastic component tensile specimen were tested.

Keywords: Wood-Plastic-Composite, Cutting Edge, Injection Moulding Process

1 Introduction

When using wood materials in combination with polymer materials the structure of wood often is subordinately and wood is used as flour filling in polymers [1, 2]. This is related to its low density as well to the special ability of wood to bind CO_2 while growing. Therefore, wood has a low environmental footprint compared to other filling and reinforcement materials e. g. based on glass or carbon. Using wood fibres in polymers

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addresses the reinforcement of the compound but is often related to difficult processing by means of thermal damage of the fibres [2]. Another way is to use solid wood plates. The advantage is the natural composite structure of wood base element: celluloses as fibres and lignin as matrix. For this no extra processing of the raw material is necessary and the cost to performance ratio becomes economically relevant for a wood-plastic application.

2 Manufacturing of Wood-Polymer composites

When using wood as flour filling in polymers the wood raw material (flour, shavings, chips, fibres) is just mixed into the polymer granules. Typical methods to produce wood-plastic-composites (WPC) parts are the direct extrusion of profiles (US market: 98% [3]), injection moulding or pressing techniques [3].

The usage of solid wood like wood veneer in combination with polymers requires the adaption of existing processing methods. Taking the mechanical characteristic of the wood veneer into count pressing techniques become more relevant [4, 5]. The veneer and polymer films can be stacked alternately and pressed while increased temperature melts the polymer. The cured veneer-polymer-compound can be processed further.
For decorative parts thin veneer is processed in injection moulding and overmoulded as well as back-injected with rips and other supporting structures. Since this process is widely used there is a number of findings available for the process parameters and resulting (bonding) strength [6–11].

The investigation shown in this paper aims to determine influences and parameter relations of bond strength between solid wood and polymer material based on a varying bonding agent ratio and wood surface characteristic. For this firstly the bonding strength between wood veneer and polymer using a bonding agent are analysed. After determining the optimal processing parameters for this, the influence of a shear cutting surface on the bonding strength is evaluated. The results of all the experiments are shown and discussed below.

2.1 Shear cutting of wood materials

In this section the shear cutting process and the resulting characteristics on wood cutting edge surface topology is described.
The shear cutting process is described based on DIN 8865 shown in Figure 1. A punch is moved against the die with a specific die clearance. This clearance influences the resulting cutting force, the wear of the tool and the workpiece edge cutting quality. Additionally, a blank holder can be used when materials tend to move or bend when processed.
Advantages of the process are the short cycle times and the overall low cost. A major disadvantage is mainly the tool based method which includes wear and therefore maintenance intervals.

The shear cutting of wood is not highly investigated yet due to the process is not typically used for wood materials as Wagenführ et al. [12] and Kollmann [13] said.

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Defining the forces and the resulting surface geometry the process can be adapted for the following injection moulding for wood-polymer parts. To show basic findings is targeted by the experiments presented in this paper.

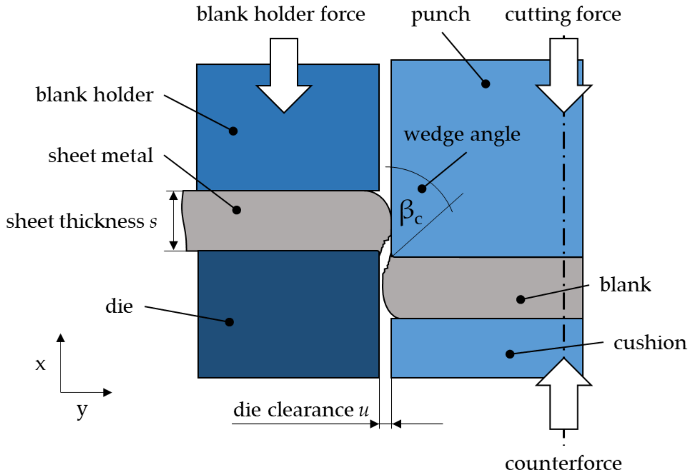

Figure 1 Basic terms of shear cutting process

Wood has low density due its capillary and therefore hollow structure. When cutting, the force is applied orthogonal to this tubes and the structure is compressed and damaged. In comparison to metal material the mirco sectional analysis shows significant fractures at the cutting edge (see Figure 2).

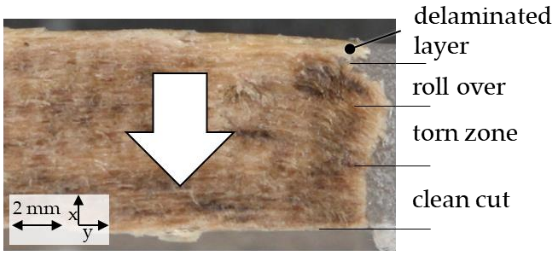

Figure 2 Cutting edge geometry of solid wood in the shear cutting process

The cutting edge geometry shows different sections. A delamination in the first millimetres can be detected. The fibres in this section spring back when the load maximum is exceeded and tearing appears. This effect leads to a delamination between the fibres torned and the fibres expanded and bended. It is observed that the torn zone where fibres tear apart is situated behind the roll over zone where fibres are bend. A clean cut appears at the lower cutting section. It is assumed that the fibres are first compressed and stretched to their maximum followed by a clear cut.

2.2 Influence of bonding agent

Combining the two different material categories of wood and polymers the bonding strength can be increased by using bonding agents. There are findings available for maleic

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anhydride grafted polypropylene (MAHg-PP) especially when using polypropylene (PP) material [3, 14, 15]. This thermoplastic polymer type is often used in polymer parts due to its specific mechanical characteristics [16]. Polypropylene belongs to the group of polyolefins and is partially crystalline and non-polar [17]. To react with a joining partner, the accessible active molecular groups are required. Such groups are not available in untreated polypropylene. When using maleic anhydride grafted polypropylene (MAHg-PP) as a bonding agent a chemical connection can be achieved [18].
The achievable strength of polymer and wood are influenced by the wood quality, surface structure, material parameters like moisture content, etc. Therefore, we decided to evaluate the optimal bonding strength on the wood veneer and polymer used specifically in this study.

2.2.1 Experiments on bonding strength depending on the bonding agent

The polypropylene type BJ356O manufactured by Borealis® and ExxonMobile®'s bonding agent ExxelorTM PO 1020 containing approximately 1 wt.-% of maleic acid [19] were used for investigations.
The bonding strength was determined as shear strength in 3-point-bending specimen (see Figure 3). The specimen geometry offers a large connection area which suitable to test thin veneer coated with polymer.

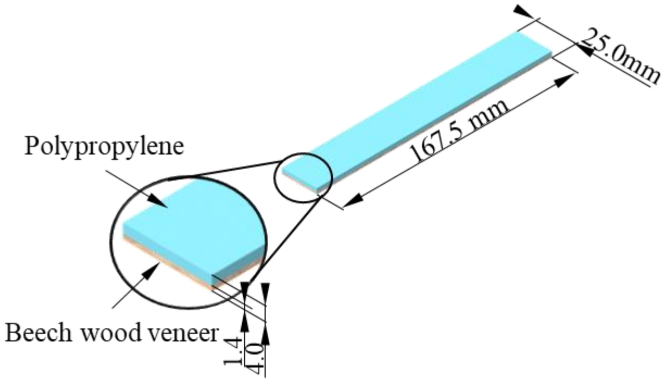

Figure 3 Polypropylene-wood veneer bending specimen

The aim of the experiment was to achieve the optimal bonding agent content and melt temperature of the plastic melt by varying the values in three steps according to Table 1.

Table 1 Variation of the adhesion promoter content and the melt temperature for the initial tests

	Melt temperature T in [°C]	**Bonding agent content m in [wt.-%]**
Lower level	190	5
Basic level	200	10
Higher level	210	20

Figure 4 shows the influence on the bending strength of the variation of melt temperature and bonding agent content. It can be assumed that the bond strength decreases with

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increasing temperature. This can be explained by the convergence of the melt temperature to the temperature of maximum reaction between beech wood and oxygen at 210 °C which leads to higher depolymerization of cellulose [2]. This means that fewer free hydroxyl groups are available with which the bonding agent can react.

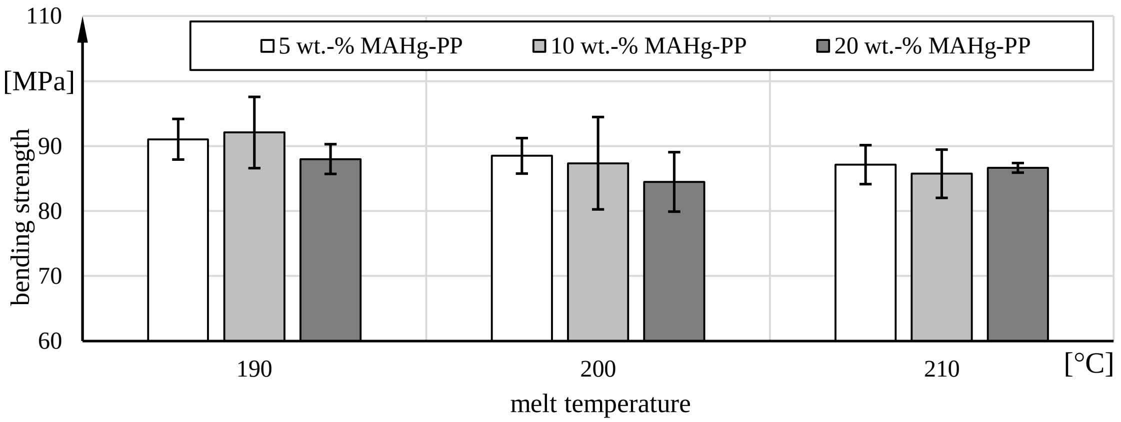

Figure 4 Dependence of bending strength on melt temperature and bonding agent content

At adhesion promoter contents of 5 and 10 wt.-%, the strength is approximately the same. It decreases at the highest adhesion promoter content. This indicates a saturation already reached at 5 wt.-% adhesion promoter content. A further increase even has a strength-reducing effect.

For the following investigations an adhesion promoter content of 5 wt.-% and a melt temperature of 190°C is used.

2.3 Influence of shear cutting surface characteristic on bond strength in tensile specimen

To determine the influence of the shear cutting surface characteristic different material and tool parameters in the shear cutting process are used. The influence of two different wood types beech and oak are addressed due to their different structure and therefore expected varying behavior when cut.
Secondly the determination of the bond strength values is addressed in this study. For this purpose, the cut edge of the wood material was butt-moulded. For the achievement of a composite strength, possible interlocking effects between polymer and cutting edge of the wood material are to be used. The preceding shear cutting process is used to display different cut edge characteristics of the wood material. The quantification of this influence is determined by means of tensile test force.

For this two-step process the specimen dimensions are shown in Figure 5. A thickness of 5mm solid wood material was choosen to enlarge the bonding surface. When manufacture the wood-polymer specimen the dimension ratio of both components is nearly the same. This is important for tensile testing to force the bonding area to fail rather than the material.

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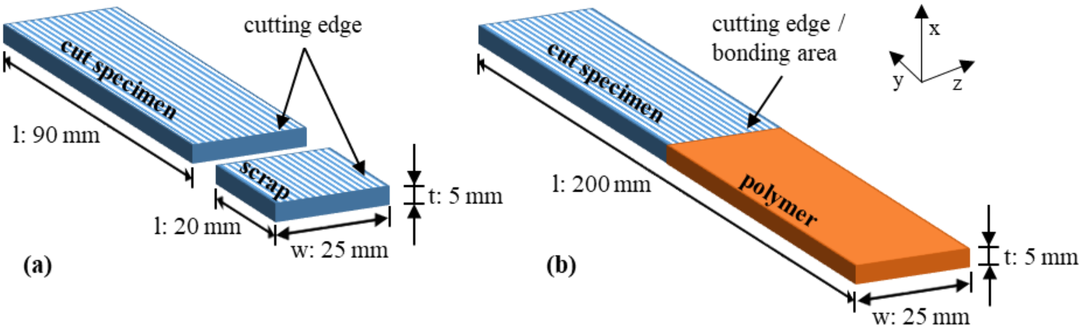

Figure 5 Shear cutting (a) and injection moulding (b) specimen

The process parameters are shown in Table 2. Depending on the experiment different parameters are listed and varied.

Table 2. Processing parameters for shear cutting and injection moulding process

Process parameter	**Symbol & Units**	**Value**
I. Shear cutting process		
Wood specimen dimensions	w x l x t in mm	25 x 110 x 5
Shear gap	u in mm	0.016 (u/t: 8%)
Cutting speed	v_c in mm/min	500
Cutting condition	T_t in °C	23°C at 65% rH
Grain orientation	γ_c in °	90
Wood type	-	beech (BE); oak (OA)
Preconditioning (according to EN 13483-1)	ω in %	9; 15
Tool shape/cutting angle	α_c in °	straight: 0; angled: 20
Quantity of specimen per series	-	10
II. Injection molding process		
Injection molding specimen dimensions	w x l x t in mm	25 x 200 x 5
Melt temperature	T in °C	190
Max. pressure	bar	760
Holding pressure	t in s	19 s at 760 bar; 6 s at 0 bar
Mold temperature	T in °C	60
Cooling time	t in s	60
Bonding agent ratio	m in wt.-%	5
Quantity of specimen per series	-	10

2.3.1 Shear cutting properties of wood specimen

The shear cutting process was realized on a self-constructed shear cutting tool. The tool was mounted on a press which enabled the movement of the punch while recording the target value of the cutting force. To determine material related dependencies the wood type

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and the wood moisture were varied in two different values. Using different wood types show the influence of specific wood structures. By varying the moisture of the wood specimen the cutting force is influenced directly. In shear cutting process basic parameters like the shear cutting gap and cutting velocity were held constant while the shear tool geometry was varied from straight to angled. The different tool shapes lead to different cutting edge geometries and therefore high influence on the bonding strength was expected.

The values reached for oak and birch are constantly on the same force level when using the same process parameters. A comparison of values for the two different cutting tools shows that using a drawing cut is a reliable method to reduce cutting forces around -19% for both wood types. This is related to the cutting mechanism: the straight cut (pushing cut) applies forces over the whole cutting edge at the same time. A force peak is therefore generated. The angled cut (drawing cut) conversely applies forces per section which is lower. Also it can be detected that the deviation of the overall values can be reduced for angled cuts.

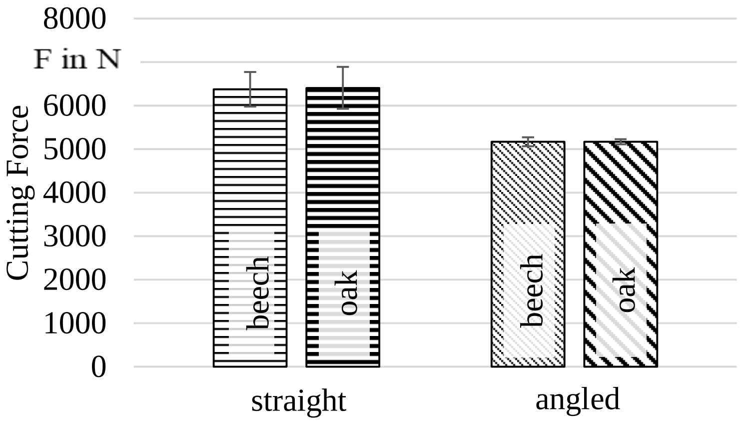

Figure 6 Influence of tool geometry on cutting force

Tool geometry
straight, angled
Specimen thickness
5.0 mm
Testing temperature
23 °C
Cutting speed
500 mm/min
Shear gap
0.016 mm
Wood type
beech, oak
Preconditioning
moisture ω: 9 %

The analysed cutting force values for different wood moistures showed no significant difference. This could be related to weak conditioning. The moisture content of 9 % and 15 % were chosen to show a high difference in mechanical behaviour. Usually this difference is adequate to modify the strength properties of wood material. The specimen geometry could have an influence on the fibre saturation. Moisture is transported longitudinal to fibre direction which is a long distance in the used specimen. The moisture can differ therefore in different positions of the specimen.

Table 3 shows section views of the cutting surface and cutting edge on different specimen. As described in 2.1 the upward specimen side shows a thin delaminated layer followed by a bend torn zone and a compressed clean cut section. The height of the torn zone is larger when an angled cut is used. This is related to the cutting mechanism: while a straight cut applies forces over the whole cutting edge, the angled cut only applies force to a punctual point of the specimen. The force is therefore higher for the individual section and the torn zone enlarges. The angled cut shows therefore higher material damage by fibre bending.

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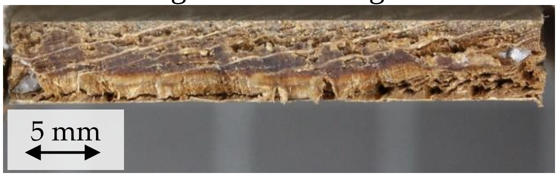
Table 3 Cutting edge and surface characteristics for beech and oak (ω: 9 %)

beech	oak
cutting surface - straight cut	cutting surface - straight cut
	
cutting surface - angled cut	cutting surface - angled cut
	
cutting edge – both cutting shapes	cutting edge - both cutting shapes
	

The cutting edge of beech shows a lower amount fibre breakage and fringe sections. For both tool geometries the cutting edges of both materials showed no clear difference.
Comparing the micro sectional views, it turned out that the reproducibility of the cutting edge is low. The individual wood types show specific breakage behavior but no identical cutting edge and surface. This is related to the natural origin of wood as well as to the fibre structure. The structure of the single specimen differs slightly so the cutting edge is differently pronounced depending on the ratio of hard and soft proportion (early/latewood).

2.3.2 Bonding strength of wood-polymer tensile specimen

To show dependencies of the bonding strength the cut wood specimen where moulded with MAHg-PP in a tensile test form. The target value was the bonding strength F in N/mm².

To analyse the bonding area microsections were made shown in Figure 7. It turned out that the cutting edge of oak material tend to close fully by the injected polymer material. Therefore, no interlocking effects by undercuts occur.

Figure 7 Microsectional view of beech (l.) and oak (r.) plastic specimen

The results can be seen in Figure 8. Firstly, the high deviation of values needs to be mentioned. Therefore, no significant factors and values could be detected. But as a trend it

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can be said that oak showed slightly lower values. It cannot make any statement about the dependencies of the tool and surface geometry of the wood on the bonding strength in combination with plastic polymer.

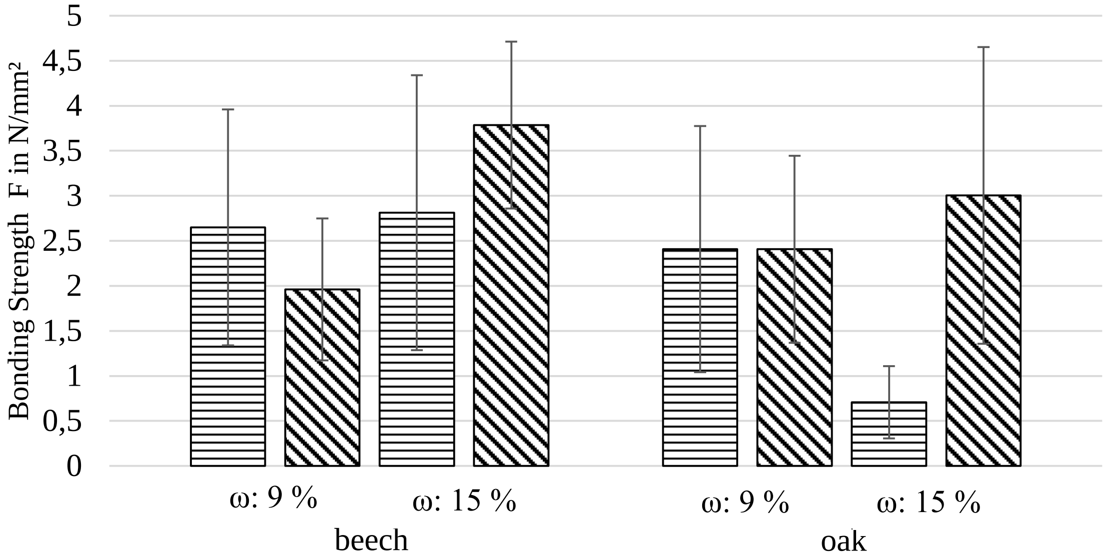

Figure 8 Tensile force of wood-plastic joint

The overall values are low in comparison to the strength in the individual materials. The chemical bonding seems to be low. When manufacture the specimen it could be detected that the ejectors of the injection moulding mould are positioned on each material side of the specimen. Therefore, in the demoulding process a bending force in the joint area was applied. The specimens were pre-damaged by this process.

Conclusion

There were results shown for the shear cutting of 5 mm solid wood specimen and the resulting bonding strength in wood-plastic-composites.

For the shear cutting process it can be said that lower cutting forces appear for drawing cuts but higher material deformation and damage occur. The influence of wood moisture content could not be examined. There is no difference in the forces for beech and oak wood material. The analysis of the surface topology needs to be extended e.g. by roughness values. By doing so the possible interlocking effects could be predicted.

In the further investigation on the bonding strength the values showed extremely high deviations so no significant parameters could be found. The original question of the influence of the shear cutting edge geometry on the bonding strength could not be answered.

The investigation showed that the specimen geometry used was not expedient. In future investigations it is planned to use a combination of a higher bonding surface area and tensile specimen. This can be reached by enlarge specimen size but also by overmould the wood specimen not only by a butt-joint but from both sides. This also allows a better resistance against bending forces which may be applied in demoulding processes.

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